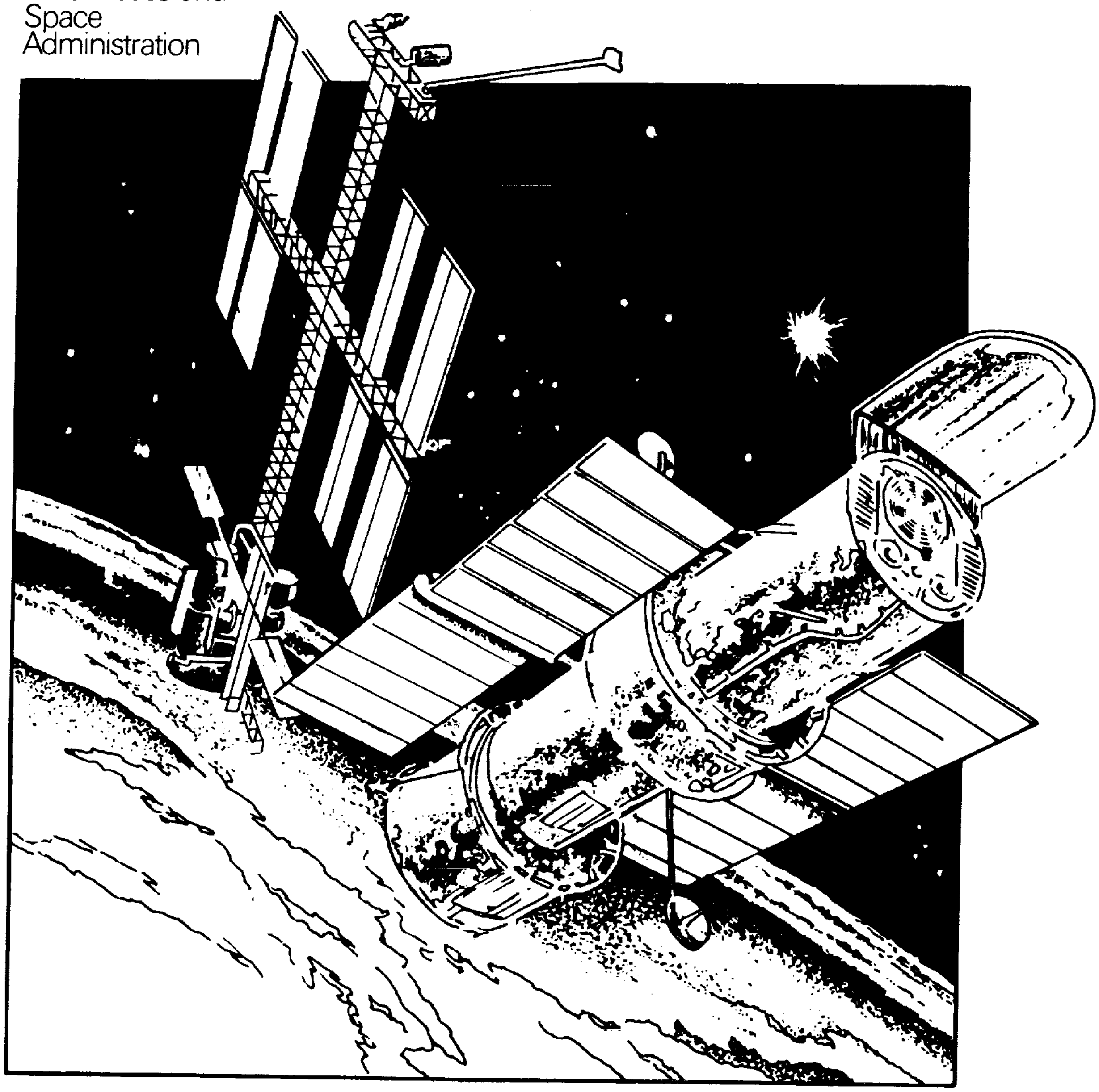
Volume 3
Satellite Servicing from the Space Station

NASA
National Aeronautics and Space Administration



Astrophysics Utilization of the Space Station

(NASA-TM-107831) WORKSHOP ON ASTROPHYSICS UTILIZATION OF THE SPACE STATION. VOLUME 3: SATELLITE SERVICING FROM THE SPACE STATION (NASA) 35 p

N92-70717

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Z9/18 0091464

ASTROPHYSICS AND THE SPACE STATION

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VOLUME 3

SATELLITE SERVICING FROM THE SPACE STATION

The idea of orbital servicing of satellites is not a new one to the Space Agency. The first significant attempt was a result of a launch-phase catastrophe during the Skylab mission. In that case, repair planning occurred only after the mission-threatening problem became evident. Because of the fatal nature of the problem, the emergency planning was performed at a high intensity and cost and at a significant risk. When the Skylab repair mission succeeded, the idea of in-orbit repair moved from concept to reality.

The advent of the Space Shuttle and the Multimission Modular Spacecraft (MMS) made orbital servicing more feasible and practical. With man in the orbital loop and a modular, repairable spacecraft, in-orbit satellite servicing concepts and the other conventional aspects of a mission were developed simultaneously. Planned servicing also offered the potential of lower cost, less panic, and less risk of failure. This concept was demonstrated successfully during the Solar Maximum Repair Mission.

Now, satellite servicing is maturing to its full potential. It is an integral part of the design of each member of a fleet of new astronomical observatories planned (Advanced X-Ray Astrophysics Facility and Space Infrared Telescope Facility) and under development (Hubble Space Telescope and Gamma Ray Observatory). The Space Station has the potential to service the observatories more effectively and make servicing practical for a broad range of platforms. The Space Station offers enhanced servicing capability with long servicing visits.

Benefits of enhanced servicing include:

- Repair/replacement of failed subsystems (in orbit or after retrieval/return to earth)
  - ensures against premature termination of mission
  - allows more risk acceptance during mission development.
- Technological upgrading/replacement of obsolete equipment
  - upgrades instruments in telescope focal planes
  - upgrades subsystems to improve performance.
- Platform support
  - enables reuse of spacecraft (experiment hardware exchanged in orbit or on ground)
  - allows spacecraft (platforms) to be amortized over several missions
  - allows experiment hardware to be upgraded and reused.

These applications, beyond simply fixing something that does not work, provide a vastly greater return on our economic and scientific investments in space research.

The purpose of Volume 3 is to define servicing concepts and requirements for both the Space Station and its satellite users so that this capability can be best utilized by the astrophysics community. Although astrophysics missions are well-suited to servicing concepts because of the frequent use of a 28.5-degree orbit (compatible with the Space Station), most of the discussion in this volume has broad applications.

SATELLITE SERVICING IN THE ASTROPHYSICS PROGRAM

For astrophysics, the present is an opportune time to be planning for the future. The Solar Maximum Repair Mission, which restored a valuable observatory for another several years of pioneering research, convincingly demonstrated the crucial role of satellite servicing in a successful astrophysics research program in space.

Planned satellite servicing in space is a major new capability with profound significance for the future of astrophysics. Indeed, routine orbital servicing is every bit as important to our science planning as advanced detector technology. Such servicing may be considered a new "technology", for it will mandate technological advances in fluid transfer and other servicing techniques.

The emergent capability to maintain, repair, and retrofit our instruments and spacecraft in space can shape the course and character of astrophysics research through the rest of this century and into the next. With optimism, we foresee the exploitation of this new capability in the Space Station era. Furthermore, we anticipate great progress in astrophysics research as our facilities gain extended lifetimes and greater versatility through in-orbit servicing.

Servicing Roles

What is the nature of this new technology, and what does it offer the astrophysics program--both practically and conceptually? Satellite servicing is the repair, replacement, or maintenance of hardware in space, a function made possible by the Shuttle, which provides access to low Earth orbit, and by the Space Station, which will provide a permanent, manned base for various activities in space. Servicing also involves resupplying consumables such as cryogens or propellants, cleaning optical surfaces, recharging batteries, making fine adjustments, calibrating instruments, and performing other "housekeeping" tasks.

In addition, servicing at the Space Station allows for an entirely new mode of operation for observatory-class facilities. Routine changeout, with or without upgrading, permits flexibility and evolution in the instruments and extends the useful scientific lifetime of the observatories in the same way that maintenance and replenishment increase their physical lifetime. Instrument changeout is more complex than simple component replacement and replenishment. It involves handling complex subsystems, alignment and, perhaps, recalibration. Such operations require the space, facilities, and time that are available with the Space Station but not with the Space Shuttle. It may also require that intricate work be carried out in the "shirtsleeve" environment of a Space Station laboratory or hangar, another capability that is impossible in the cramped quarters of the Space Shuttle.

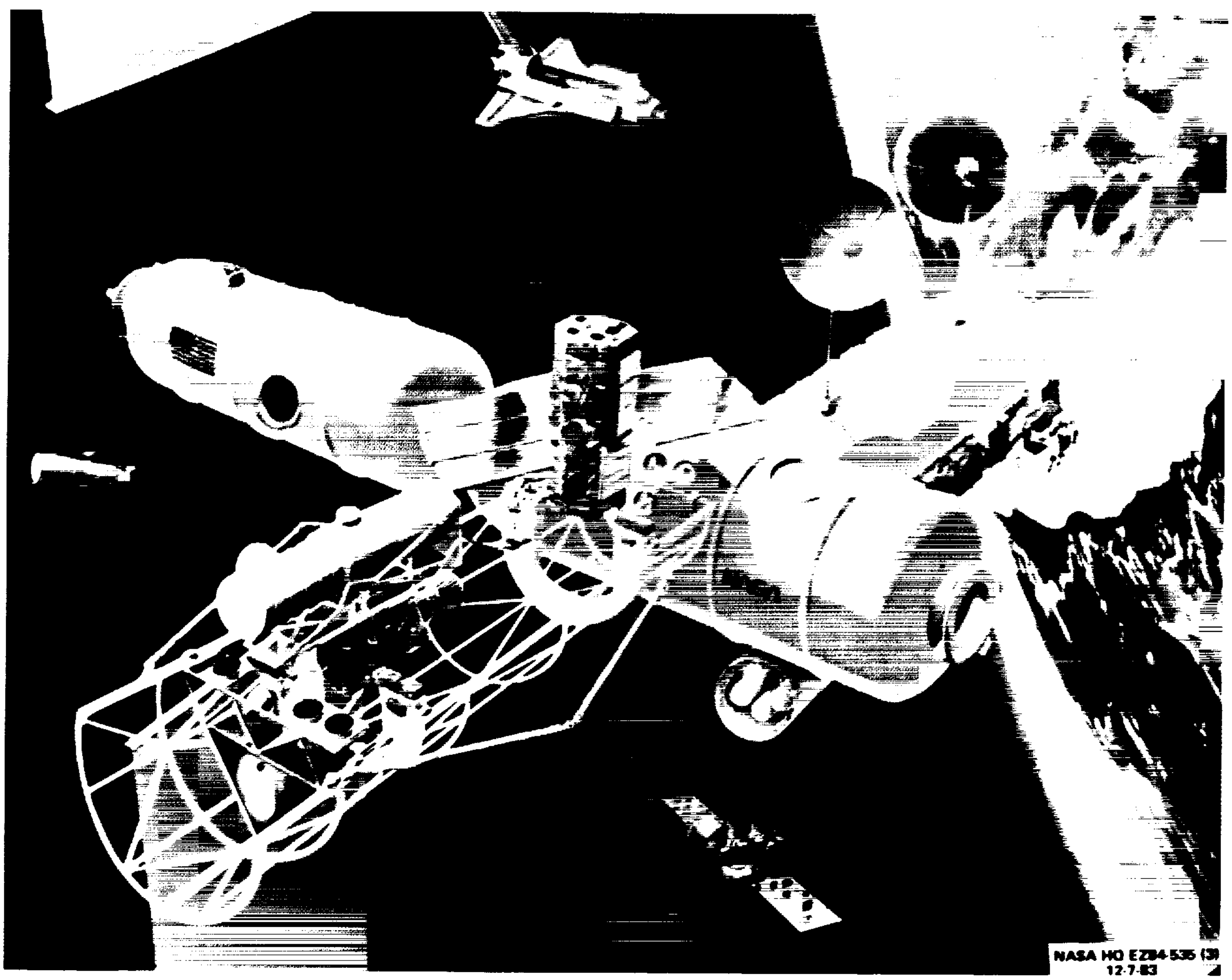

FIGURE 3.1. SERVICING ASTROPHYSICS MISSIONS AT THE SPACE STATION

This picture shows one concept for servicing spacecraft and astrophysics missions at the Space Station. The Solar Maximum Mission is shown in the Flight Support System (FSS) used in the Solar Maximum Repair Mission.

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From our experience in the past Skylab era as well as the Solar Maximum Repair Mission, we perhaps conceive of satellite servicing as a function performed by an astronaut-mechanic equipped with an Extra-Vehicular Activity (EVA) tool kit and some special mobility aids and grappling devices. For the Space Station era, however, this "Mr. Goodwrench" concept is too simplistic. We contemplate at least four major, complex servicing roles for astrophysics missions in the near future. The Space Station should be the nexus for all of these functions.

Repair

The most readily apparent servicing function is the repair or replacement of failed or degraded parts. Failures at the system, subsystem module, component, or piece-part level jeopardize every mission. The best design in the world, complete with redundant systems in all critical areas, does not guarantee against random failures or limited life-cycle parts in today's complex instrumentation. Given the fact that some failures and wear-outs are inevitable, the challenges facing us as we plan astrophysics missions are to identify repairable and/or replaceable elements, develop a servicing philosophy, and design our hardware appropriately to implement that philosophy. That is, we must make those serviceable elements accessible and readily manageable in space; we must develop standardized, rather than customized, parts and interfaces; and we must provide the capabilities needed in orbit for EVA, shirtsleeve, automated, and remote servicing tasks. The Multimission Modular Spacecraft, for example, is designed for repair. Although not so designed, parts of the Solar Maximum observatory's instrument complement proved repairable with some ingenuity.

No longer must we use hindsight to determine how to repair space hardware, however. The Shuttle and Space Station give us the opportunity to use foresight and careful design to restore failed or degraded parts, thereby extending the useful life of our spacecraft. By making our instruments easily serviceable in orbit, we may also be easing the task of system integration and testing on the ground, since ground-accessibility will also be improved. Both the Shuttle and the Space Station will, however, continue to play important roles in servicing because of the limitations on Space Station access to missions having a different orbital plane. For a mission like Hubble Space Telescope (HST), the periods for possible Space Station access and service are spaced at several year intervals. During intermediate times, only the Shuttle can be used to rescue and fix a "sick" space telescope. Thus, the Space Station will be the regular service station and the Shuttle the "breakdown van" of the 1990's.

Maintenance

A second servicing role is the maintenance of our orbital observatories, major new facilities with expected operational lifetimes of 10 to 20 years or longer. This spacecraft class includes the Hubble Space Telescope

(HST), the Advanced X-Ray Astrophysics Facility (AXAF), the Gamma Ray Observatory (GRO), and the Space Infrared Telescope Facility (SIRTF), as well as the Solar Maximum Mission (SMM). There is compelling justification for servicing these observatories, because of our large investment in their development and because of the scientific necessity for their existence. The orbital observatories embody our aspirations to understand the origin and history of the universe, and they will be our prime tools for discovery in the years ahead.

Upgrade

Servicing satellites involves not only routine maintenance, resupply of consumables, and repair of broken parts, but also periodic upgrading of the instruments with new technology. The mirrors themselves will be the finest possible, with unprecedented quality, and we do not expect them to become obsolete. However, detector technology advances so rapidly that it is desirable to maintain state-of-the-art instrumentation at the focal plane. The new servicing capability enables us to upgrade observatories by exchanging focal plane instruments as technology yields improved sensitivity and resolution.

Since discovery keeps pace with technology and each increase in sensitivity reveals more faces of the unknown, upgrading our major observatories is crucial to astrophysical research in space.

Another innovative servicing role is the support of modest-scale missions in the Explorer or Proteus class. We envision a fleet of standardized free-flyer buses capable of carrying several different payloads, with each bus having a lifetime of 10 to 15 years. Like the Multimission Modular Spacecraft currently used for observatory-class payloads, such as Landsat and Solar Max, the reusable bus would consist of standardized serviceable parts and a standardized instrument interface. An instrument set mated to the bus would operate for 2 to 3 years and then be removed, in orbit, for replacement by a new payload of instruments with perhaps an entirely different research agenda.

Delivery and Retrieval

A fourth significant servicing role is the delivery and retrieval of satellites. The use of space-based, reusable, low and high energy transfer vehicles to deliver newly launched spacecraft from the Space Station to operational orbit will extend the cost benefits provided by the Shuttle as a delivery vehicle. The use of the Space Station as a transportation node will be further enhanced by efficient retrieval of malfunctioning or obsolescent spacecraft and transport to the Space Station for maintenance, repair, or retrofit. An additional servicing benefit is the cost-effective reboost of functional spacecraft into operationally more effective orbits by reusable transfer vehicles, based on the Space Station, rather than by dedicated Shuttle missions.

As the new servicing technology evolves, so will our philosophy of mission planning. Instead of designing a spacecraft to accommodate pre-selected scientific objectives, we will be able to tailor science to the flexible capabilities of multimission spacecraft. We will also be able to improve our capabilities to meet future mission requirements by upgrading these serviceable spacecraft. We envision using the same bus, with no redesign, for different kinds of missions, such as Sun pointing, stellar pointing, Earth pointing from low-Earth orbit, and Earth pointing from geo-synchronous orbit. A versatile, serviceable spacecraft offers many mission opportunities. Standardization of certain spacecraft elements and designs need not limit our imaginative planning for astrophysics research in space.

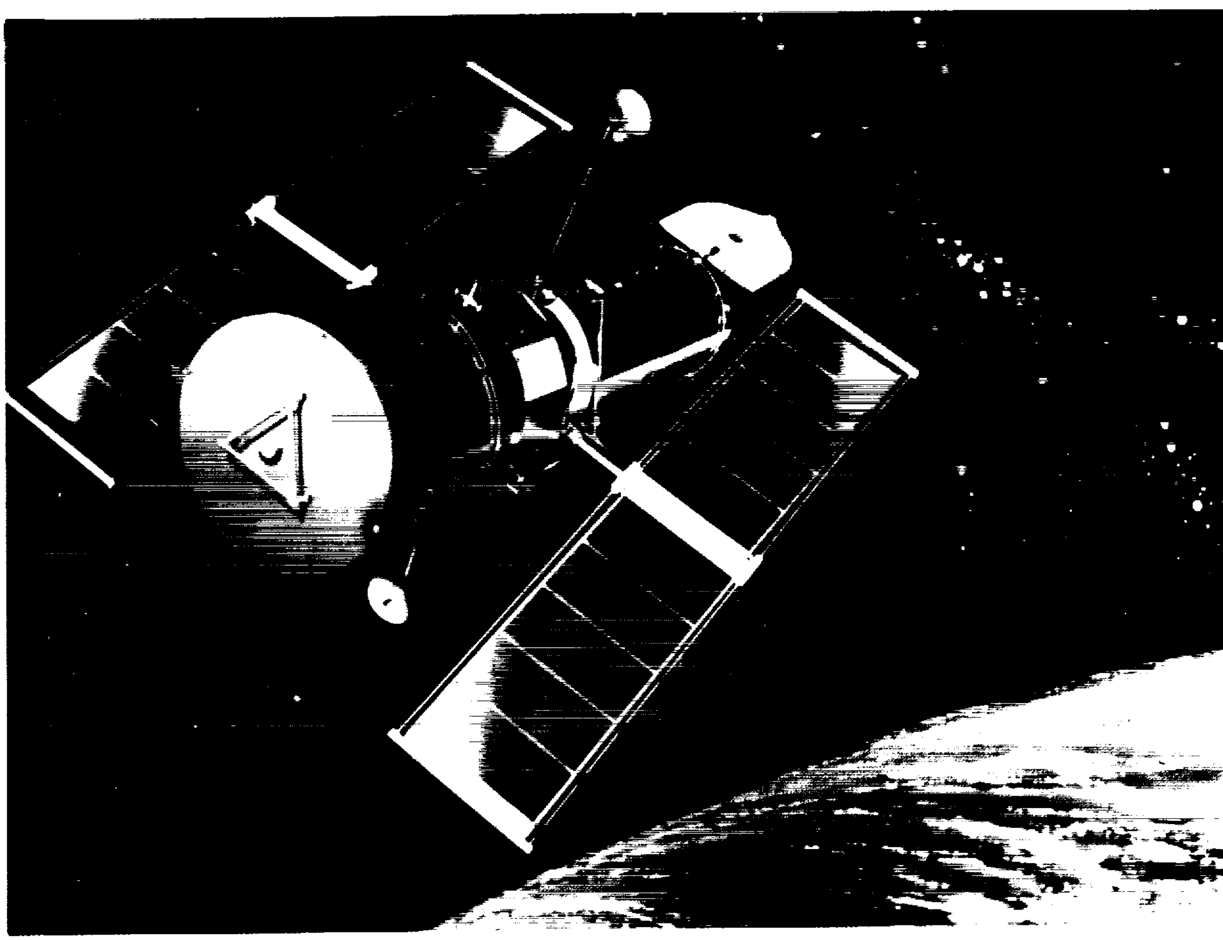

FIGURE 3.2. THE HUBBLE SPACE TELESCOPE (HST)

In addition to its scientific instruments, the major spacecraft systems of HST are modular and designed to be replaced in orbit. Much more of HST becomes serviceable at the Space Station. HST and the other observatories are described in the Appendix to this volume.

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Servicing Philosophy

The thrust of all these servicing functions--repair, observatory maintenance, mission support, and orbit transfer--is the same: to use and maintain our capital assets in space. Satellite servicing is the key to gaining the most value from these facilities. Rather than accept failures that convert sophisticated spacecraft into expensive junk, we will adapt and repair our assets. Furthermore, the focus will be on space repair operations with ground return as a last resort. This will help to avoid subjecting flight equipment to the hostile environment of a round trip back to space, avoid nonessential repairs, and minimize a large support staff on the ground.

The attractive option, then, is to take advantage of the new servicing capabilities afforded by the Shuttle and Space Station. It is time to implement a reasoned servicing philosophy in the design of spacecraft and scientific instruments. It is also time to specify the standardized interfaces and servicing requirements for spacecraft design and to identify the servicing resources needed on the Space Station.

Logistics Standardization

Inherent in the concept of satellite servicing is the concept of logistics standardization. It is very expensive to service one-of-a-kind components custom-designed for a particular mission. The logistical problems of stocking unique parts and training crew members to service each different part make standardization attractive, at least for elements common to many spacecraft (e.g., subsystems, star trackers, batteries). On the other hand, scientific instruments by their very nature obviously are unique and, except for interfaces, do not lend themselves to standardization. Furthermore, by common spacecraft bus, subsystems, and component sharing, more room will be available for storing unique, replaceable scientific instruments aboard the Space Station. Standardization of serviceable spacecraft elements is another way to improve funding for science instrumentation through common and shared use of spare spacecraft equipment.

Serviceable space systems are already taking logistics standardization into account. The Space Transportation System has to sustain an inventory to support the Space Shuttle and its elements. The Space Telescope is similarly committed to support its system, as is the Multimission Modular Spacecraft. To ease its logistics problems, the Space Station will go one step further and attempt to use common elements across all its modules.

New spacecraft should use systems, subsystems, and components from existing inventories or from newly defined Space Station and space platform components where feasible. In some instances, market conditions will force new designs, which can be constrained to meet existing interfaces and to provide new capability. If these elements are not standardized, the cost of ownership of long-lived systems will so dominate the budget that new development opportunities will be curtailed. The astrophysics program must move toward standardization in spacecraft design, at least at the interface level, if we are to reap the most scientific benefit from the new servicing technology.

Effective spacecraft servicing has the promise of dramatically increasing our scientific understanding. With sophisticated observatories in space and long periods of observation, it may be possible in our lifetimes to exceed the number of all previous discoveries about the nature and history of the universe. Orbital servicing can extend mission lifetimes threefold or more, enabling more scientific investigations through reuse of existing facilities. In this context, use of observatories in space would more nearly resemble the continuous use and reuse of observatories on the ground.

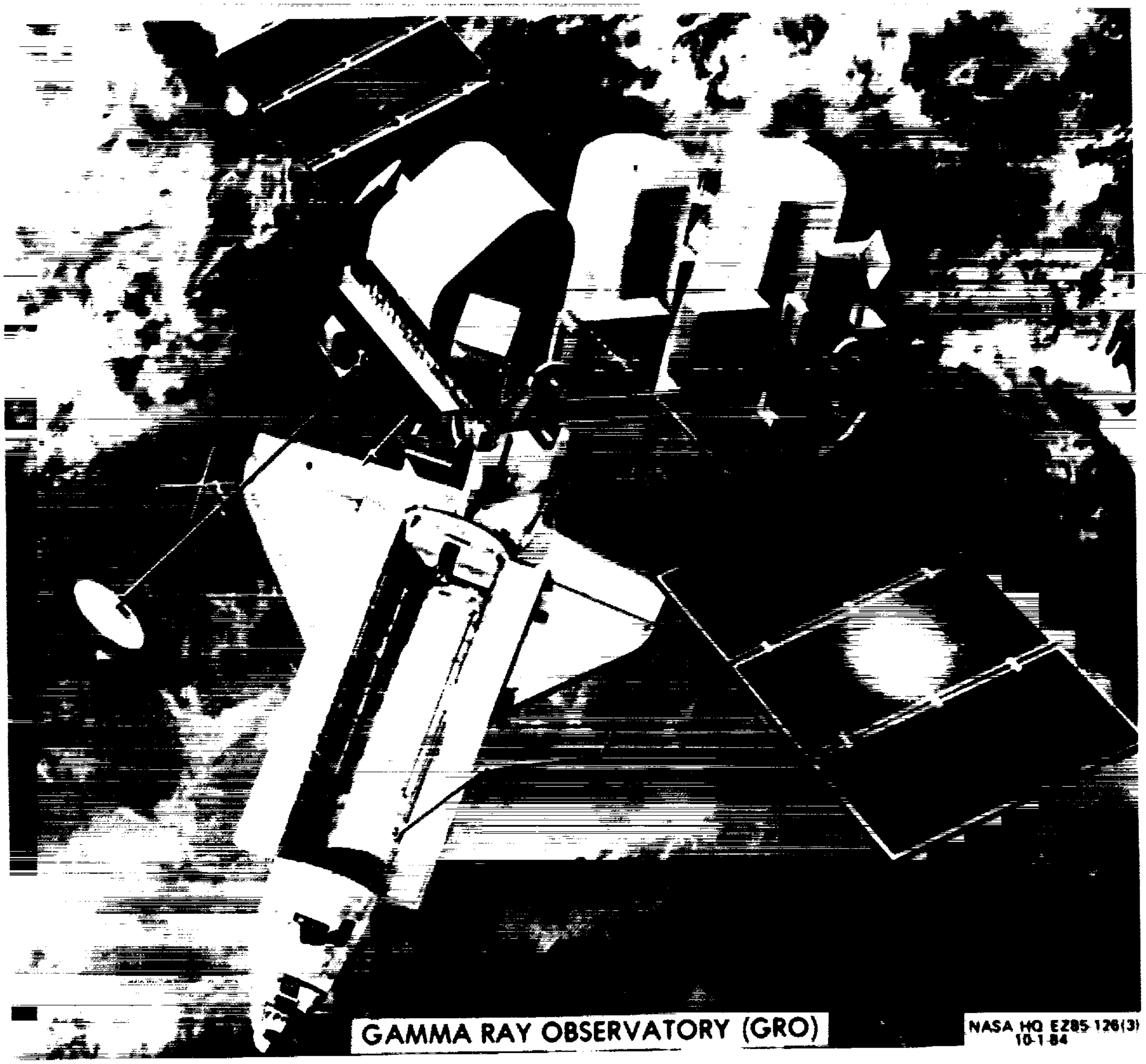

FIGURE 3.3. THE GAMMA RAY OBSERVATORY (GRO)

Low altitude is an important scientific requirement for this mission. To extend the mission's lifetime, the propulsion system can be refueled in space.

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Human Productivity

Besides conserving hardware by extending the useful lifetimes of existing satellites, orbital servicing conserves an equally valuable commodity: human effort. The design, construction, and use of a scientific satellite involves years of work by many people. In particular, scientists may devote 10 years of their career to seeing a concept brought to fruition. If the satellite or instrument then fails, whether or not they foresee the reasons, those people have squandered their own most valuable resource--time. Thus, satellite science offers impressive rewards, but only with great risk.

By repairing and improving satellites, it is possible to safeguard this personal (and national) investment. Lessened risk also will enable more scientists to become involved in space science, to the great benefit of astrophysics. Furthermore, by use of multi-purpose platforms, spacecraft development schedules will no longer pace the development cycle; proven instruments may fly on much shorter time scales than at present. In-orbit servicing inevitably leads to optimal use of scientific instruments by preventing loss or diminution of capability. Our human scientific resources also will be better utilized.

As both the scientific objectives and the requisite instruments for modern astronomy and astrophysics grow increasingly more complex and more expensive, we need to develop more economical means to achieve our scientific goals. Orbital repair, maintenance, and upgrading hold promise, both economically and scientifically, for enabling us to make the discoveries that surely await us.

SATELLITE SERVICING AND THE SPACE STATION

While the Shuttle has made satellite servicing possible, the Space Station offers dramatically improved capabilities and resources for performing repair, maintenance, and refurbishment activities in space. To appreciate more vividly the advantage of a Space Station service center for astrophysics missions, consider the following analogy.

For some 40 years, the Palomar Observatory has been one of the premier astronomical research facilities in the world. Its longevity despite the explosion of high technology is due to regular maintenance and periodic upgrading to introduce new technology in the focal plane. The value and versatility of the observatory have kept pace with advances in detector and computer technology, and through continuous operation for four decades the observatory has contributed vastly to our knowledge of the universe. Palomar is a major asset for the nation and the scientific community; the same can be said of our new orbital observatories.

The Space Station permits servicing an orbital telescope in a manner comparable to the way the Palomar Observatory is maintained: with more time for servicing at a relaxed pace, greater flexibility in work schedules and supply delivery, and a relatively clean environment. The Space Station should ultimately include a shirtsleeve environment hangar, which will make it possible to perform major refurbishment in space and thereby avoid the attendant costs and risks of returning spacecraft to the ground.

As we plan for servicing at the Space Station, we must answer the following questions for each candidate mission: What elements or subsystems require routine servicing or maintenance? What parts are most likely to fail? What can be fixed? What can be replaced? What can be done remotely or by automation? What can be done by EVA? What must be done in a shirtsleeve environment? What kind of additional science can we do with in-orbit servicing capabilities? Identifying repairable and replaceable parts is the first step toward designing a serviceable spacecraft and a service center that meets the customer's needs. These servicing and design requirements are described in considerable detail later in this volume.

Maintenance Echelons

We also must develop a maintenance philosophy that guides our design, best serves science by assuring long-lived missions, and most economically utilizes the Space Station for servicing. Here we can learn valuable lessons from past experience in space and also from commercial and military organizations with similar maintenance and logistical demands to keep their hardware in service.

In particular, the military concept of maintenance echelons is applicable to satellite servicing in space. First-echelon maintenance, the least complex level, involves elements designed for repair-by-replacement. These tasks may be accomplished in space by EVA, remotely operated devices, or automation; they typically involve removal and reinstallation of units equipped with quick-disconnect features, such as MMS-type modules. Second-echelon maintenance involves repairable or replaceable elements that are not necessarily designed for servicing. This task can be done by EVA and is of intermediate complexity. Servicing of the main electronics box on Solar Max exemplifies the second echelon of maintenance. In the military, these first- and second-echelon activities are performed in the field.

The third and fourth echelons of spacecraft maintenance would occur on the ground today, but in the Space Station era they could occur in a shirtsleeve environment in space. In the military, these activities are performed at a depot rather than in the field. In third-echelon maintenance, black boxes within systems would be replaced or simple tasks would be conducted on subsystems small enough to be accommodated in a pressurized module or lab, while in Echelon Four, an entire spacecraft or major subsystem would be brought into a pressurized hangar for major repair or overhaul.

By the same analogy, resupply of consumables can be thought of in echelons. Echelon 1 resupply is accomplished by fluid transfer and Echelon 2 by canister replacement, both in EVA operations. Both at Echelon 3 (subsystem fluid and canister replacement) and at Echelon 4 (system fluid and canister replacement), resupply operations occur in a shirtsleeve environment.

Preliminary studies indicate that it will be exorbitantly expensive to bring observatory-class instruments to the ground for Echelon 3 and 4 servicing. Cost estimates for full refurbishment range as high as 50 percent of the original development cost of observatory systems. Furthermore, the delicate telescopes will be subjected to G-loads, vibration, and contamination during return and landing. Just as the military strategy is to keep vehicles and systems in service with minimal downtime, so our strategy for astrophysics missions must be to keep our telescopes in space and keep them working there. While return of smaller, less complex spacecraft may be feasible, the economically practical approach to large-scale servicing is to do it in space.

The Space Station offers such an opportunity. Ideally, a Space Station service center will provide facilities for both EVA tasks (first and second echelons) and shirtsleeve tasks (third and fourth echelons) for planned maintenance, and Shuttle facilities for first- and second-echelon contingency maintenance. Missions in the astrophysics program must be evaluated to determine what maintenance planned to be done on the ground could be done in space given an appropriate Space Station environment. Development of a maintenance philosophy covering all four echelons is imperative for astrophysics missions in this new era.

THE ASTROPHYSICS MISSIONS AND THEIR SERVICING REQUIREMENTS

Survey

To develop a valid servicing philosophy for astrophysics missions, we should understand the servicing needs of the payloads and identify the spacecraft and payload hardware that can be serviced. As part of the June 1984 workshop deliberations on Astrophysics Utilization of the Space Station, the spacecraft servicing group conducted a survey to identify the servicing requirements of 24 near-term and possible future astrophysics missions. During the workshop, a panel of scientists, program managers, and satellite servicing experts convened to review the results of the survey and prepare this document for publication. As the draft was subjected to critical scrutiny, the group refined the servicing concepts foreseen for astrophysics missions and specified requirements for both the Space Station and its astrophysics users. This document represents the consensus of key members of the astrophysics community who are responsible for the planning, design, and scientific objectives of serviceable astrophysics missions.

The appendix to this volume summarizes some of the missions surveyed. (Missions selected for the study were those having, at present, the most complete technical definition. For missions not yet approved, inclusion in this report does not imply priority). The purposes of the survey were to collect detailed information about planned spacecraft/payload design and anticipated servicing tasks, and also to stimulate creative thought about taking advantage of the servicing capabilities that are possible on the Space Station.

The survey was conducted in four steps. First, a team of spacecraft servicing authorities developed a questionnaire to assess the servicing potential of each mission. Then, members of this group solicited information from principal representatives of the astrophysics community and completed a questionnaire for each mission.

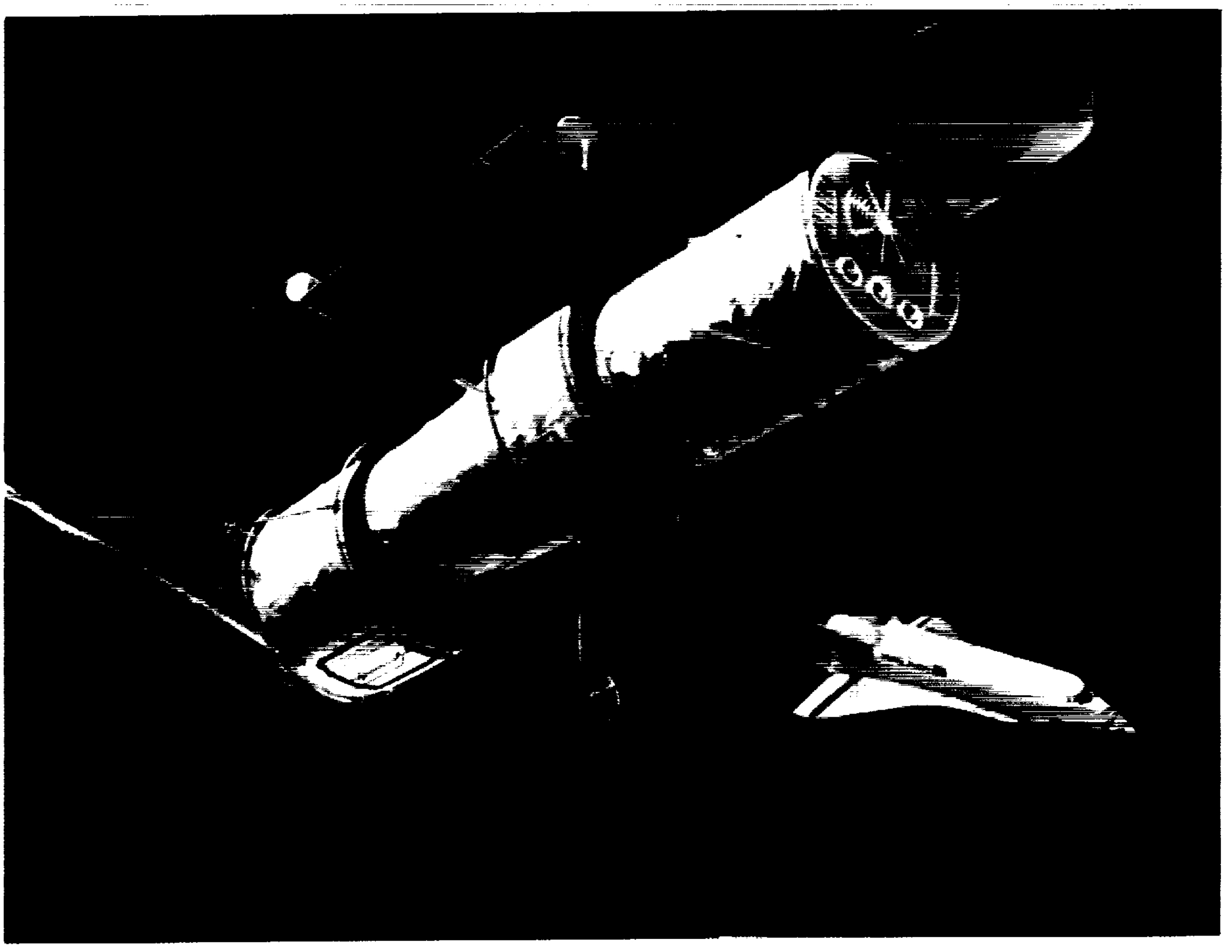

FIGURE 3.4. THE ADVANCED X-RAY ASTROPHYSICS FACILITY (AXAF)

X-ray observatories are so important to modern astrophysics that AXAF will be designed as a permanent observatory in space; it is a candidate mission for a dedicated Space Station platform.

From the completed questionnaires, the group extracted critical information and plotted a matrix of servicing functions for all missions. Results are presented here as Tables 1 through 3; Table 4 is a servicing schedule, also derived from the questionnaires. Finally, from this matrix were derived the servicing requirements of astrophysics missions and the definition of Space Station capabilities necessary to meet these servicing needs.

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Key Candidate Systems for Servicing

From the survey, we found that some spacecraft systems and components are better candidates than others for in-orbit servicing (replacement, adjustment, or repair). The key candidates for in-orbit servicing are:

- Scientific instruments that may be replaced with higher technology sensors or with instruments designed to collect different data
- Systems that require replenishment of consumables
- Limited-lifetime components expected to degrade with use
- Failures that could damage the spacecraft or limit its usefulness and for which redundancy cannot be provided
- Technologically limited equipment with a high probability of degradation
- Easily replaceable hardware, since the cost of providing the servicing capability may be low
- Orbital altitude maintenance.

Other Key Findings

An analysis of the information on the questionnaires revealed that in-orbit servicing is highly desirable for all surveyed payloads and that servicing from the Space Station has advantages over servicing from the Shuttle. Other key findings are as follows:

- All astrophysics missions studied require, or can use, some type of in-orbit servicing.
- Less than 10 percent of the missions require only contingency servicing. The rest plan routine and/or upgrade as well as contingency servicing.
- Routine servicing can greatly enhance the scientific value of a payload.
- Most missions plan first- and second-echelon servicing, with third- and fourth-echelon repair in a contamination-free, shirtsleeve work area offering the ability to reduce inventory requirements.
- To preclude the need to return observatories to the ground for major refurbishment, a contamination-free, shirtsleeve facility with good access to large systems and subsystems is required.
- Spacecraft retention and positioning systems are required for servicing free-flyers at the Space Station.
- Commonality of support systems should be a prime consideration in the observatory design.
- Modes of consumable resupply at the Space Station will include recharge from storage tanks or dewars and canister replacement.
- Ease of training for the servicing crew should also be a strong consideration.
- Leased platform services' program requirements are similar to AXAF, SIRTF, and Space Telescope except service frequency is every 6 months.

TABLE 1. NEAR-TERM AND POSSIBLE FUTURE ASTROPHYSICS MISSIONS INCLUDED IN SURVEY*

Mission	Acronym	Launch
FREEFLYERS		
Observatories		
Hubble Space Telescope	HST	1986
Gamma Ray Observatory	GRO	1988
Advanced X-Ray Astrophysics Facility**	AXAF	early 1990's
Space Infrared Telescope Facility**	SIRTF	early 1990's
Moderate and Explorer Missions		
Advanced Low Energy Gamma-Ray Explorer	ALEGRE	TBD
Astrometric Explorer	AE	mid-1990s
Cosmic	COSMIC	early 2000's
Far Ultraviolet Spectroscopic Explorer	FUSE	early 1990's
High Energy Transient Explorer	HETE	early 1990's
High Through-Put Mission	HTM	TBD
Large Deployable Reflector	LDR	late 1990's
Near Infrared Sky Mapper	NISM	TBD
Solar Corona Diagnostics Mission	SCDM	mid-1990's
Solar Maximum Mission	SMM	1980, 1984
Spacecraft Array for Michaelson Spatial Interferometry	SAMSI	early 2000's
Space Platform Interferometer	SPI	mid-1990's
Starlab	STARLAB	mid-1990's
X-Ray Timing Explorer	XTE	early 1990's
PAYLOADS ATTACHED TO THE SPACE STATION		
Cosmic Ray Nuclei Experiment/TRIC	CRNE/TRIC	early 1990's
High Energy Space Station Array	HESS Array	mid-1990's
Solar Optical Telescope	SOT	TBD
Advanced Solar Observatory	ASO	early 1990's
Solar Terrestrial Observatory	STO	mid-1990's
Superconducting Magnet Facility	SCMF	mid-1990's

*These are mostly candidate future missions; no priority is intended.
**Space Station platforms may be used as the basis for these missions to improve commonality of components and interfaces.

TABLE 2. ASTROPHYSICS FREE-FLYER MISSION POTENTIAL SERVICING REQUIREMENTS

	HST	GRO	AXAF	SIRTF	SMM	STARLAB	HTM	LDR	SAMSI	COSMIC	HETE	FUSE	XTE	AE	SCDM	NISM	ALEGRE	SPI	TOTAL
Systems Requiring Service																			
Instruments	X		X		X			X		X					X		X	X	8
Spacecraft	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X			15
Subsystems	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	18
Components	X		X	X	X	X				X	X	X	X		X	X		X	12
Systems Designed for Service																			
Instruments	X		X					X		X			X		X		X	X	8
Spacecraft	X	X	X	X	X		X		X	X	X	X	X	X	X	X			14
Subsystems	X	X	X	X			X	X	X	X	X	X	X		X	X	X	X	15
Components	X									X		X			X	X		X	6
None						X													1
Capture Technique(s)																			
OMV			X	X	X			X	X	X	X	X	X	X	X	X			12
OTV						X		X				X	X		X	X		X	7
RMS	X	X	X	X	X	X			X	X	X	X	X	X	X	X		X	15
MMU					X				X		X	X	X		X	X		X	8
Attached P/L																			0
Service Site																			
Berthing Platform (FSS)	X	X	X	X	X	X				X								X	8
Surrogate Bay	X	X							X	X		X		X	X	X			8
Attached Payload Site																			0
Shirtsleeve (Subsystem)	X		X	X	X			X	X	X					X				8
Shirtsleeve (Observatory)	X			X	X														3
In-Situ								X											1
Type of Service																			
Routine		X	X	X	X			X	X		X		X		X	X	X		11
Contingency	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	16
Upgrade	X		X	X	X		X	X		X		X			X	X	X	X	12
Maintenance Echelons of Service																			
Routine		1	1,2	1 or 3	1,2,3,4			1			1		1						
Contingency	1,2,3	1	1,2,3,4	1,2 or 4	1,2,3,4	1,2	TBD	2,3,4	1,2,3,4	1	1	1	1	TBD	1	1		3	
Upgrade	1		1	2,3,4	1,2		TBD	TBD		1		1			1	1			
Resupply Echelon																			
Routine		1	2	1 or 3	3			1	1		1,2	1	1		1	1	2		
Contingency							1			1									
Cycle of Service																			
Routine		2.25 yrs	3 yrs	1.5 yrs	2 yrs			3-6 mos	10 days		1 yr		3 yrs			1-2 yrs	0.5-1 yr		
Contingency	4-5 yrs	2.25 yrs		5-10 yrs	4 yrs		5 yrs			2 yrs									
Upgrade	2.5 yrs			5-10 yrs	4 yrs		5 yrs			2 yrs		2-5 yrs						1-3 yrs	
Consumable	none	N_2H_4	propane N_2H_4, TBD gas mix	LHe LH_2	propane	none	N_2H_4	LHe	TBD fuel LHe	LHe, LN_2	N_2H_4 CH_4,NH_3	N_2H_4	N_2H_4		N_2H_4	N_2H_4 LN_2	Solid Cryogen		
Mission Life																			
Without Service	2.5 yrs	2.25 yrs	3 yrs	2 yrs		0.5-1 yr	5 yrs	N/A	10 days	2 yrs	1 yr	3 yrs	3 yrs	5 yrs	TBD	1-2 yrs	0.5-1 yr	1-3 yrs	2 yrs
With Service	10+ yrs	4.5 yrs	15 yrs	10-15 yrs		indef.	10 yrs	15 yrs	10 yrs	indef.	5 yrs	10-20 yrs	6 yrs	N/A	TBD	5-10 yrs	3 yrs	indef.	9.5 yrs

TABLE 3. ASTROPHYSICS SPACE STATION ATTACHED PAYLOADS' POTENTIAL SERVICING REQUIREMENTS

	CRNE/TRIC	SCMF	SOT	ASO	STO	HESS Array	TOTAL
<u>Systems Requiring Service</u>							
Instruments			X	X	X	X	4
Spacecraft						X	1
Subsystems	X	X	X		X	X	5
Components			X		X	X	3
<u>Systems Designed for Service</u>							
Instruments					X	X	2
Spacecraft						X	1
Subsystems	X	X	X	X	X	X	6
Components					X	X	2
None							0
<u>Capture Technique(s)</u>							
OMV							0
OTV							0
RMS				X	X	X	3
MMU					X		1
Attached P/L	X	X	X	X	X	X	6
<u>Service Site</u>							
Berthing Platform (FSS)							0
Surrogate Bay	X			X			2
Attached Payload Site	X	X	X	X	X	X	6
Shirtsleeve (Subsystem)		X					1
Shirtsleeve (Observatory)							0
<u>Type of Service</u>							
Routine	X	X	X	X	X	X	6
Contingency			X	X	X	X	4
Upgrade			X	X	X	X	4
<u>Maintenance Echelons of Service</u>							
Routine			1	1,2,4	2,4	1	
Contingency				1,3	2,4	1	
Upgrade				1	2	1	
<u>Resupply Echelon</u>							
Routine	1	1	1		1,2	2	
Contingency							
<u>Cycle of Service</u>							
Routine	0.5 yr	0.5 yr	TBD	0.5 yr	0.5 yr	2 yr	0.5 yr
Contingency							
Upgrade							
<u>Consumable</u>	He-Xenon-Methane, Neon-CO_2	LHe Argon-Methane	Film	Film	N_2, Argon, Xenon	Solid target material, film	
<u>Mission Life</u>							
Without Service	0.5 yr	0.5 yr.	7 days	1 yr	0.5 yr	2 yr	0.5 yr
With Service	Indef.	Indef.	Years	10 yrs	10 yrs	10 yrs	Indef.

TABLE 4. POTENTIAL SERVICING SCHEDULE*

	1986	87	88	89	90	91	92	93	94	95	96	97	98	99	2000
Space Station							▽								
Free Flyer Mission															
Observatory Class															
HST	▽			●		●			●		●			●	
GRO			▽		●			●							
AXAF						▽			●			●			●
SIRTF							▽		●	●		●	●		
Moderate Class															
SMM	●		●		●		●								
Starlab										▽	C				
HTM					(launch date TBD)										
LDR											▽		●		●
SAMSI															▽
COSMIC															▽
Explorer Class															
FUSE						▽			●			●			
XTE						▽			●			●			
HETE							▽	●	●	●	●				
NISM								▽		●		●		●	
AE									▽		C				
SCDM									▽			●			
SPI									▽		●		●		●
ALEGRE										▽	●	●	●		
Free Flyer Total	1	0	1	1	2	1	1	2	6	2	4	11	7	6	6

* - data derived from questionnaire

▽ - launch

● - planned servicing

C - contingency servicing only

- In-orbit servicing can assure the design lifetime and also greatly extend the useful life of astrophysics observatories.
- Short-term missions (~0.5 years) can be extended to years.
- Long-term missions (~2 years) can be extended to 10-15 years (or longer).
- Contingency servicing may still be done from Shuttle because of orbital plane mismatches with the Space Station.

SPACE STATION REQUIREMENTS FOR SPACECRAFT SERVICING

The Space Station, planned for initial activation in the early 1990's, will provide a permanent base for routine maintenance, repair, and upgrading of free-flyer spacecraft and scientific payloads attached to the Space Station itself.

The requirements presented in this section are derived primarily from two sources: plans for future missions (ascertained by survey conducted by the spacecraft servicing group) and lessons learned from past and current experience. The feasibility of in-orbit repair and maintenance has been demonstrated well in the Skylab era, in Shuttle missions, and in the crew training activities for Space Telescope and Spacelab. The Solar Maximum Repair Mission dramatically confirmed the value of Shuttle-based servicing and set the stage for the Space Station as an orbital service center.

A concerted effort to infuse sound lessons learned into futuristic planning is necessary if we hope to use the Space Station for our optimal benefit in astrophysics research. Many servicing concepts and techniques have been evaluated in 0-g and 1-g simulations. Also, proven hardware exists for a variety of servicing functions, and a modular, standardized spacecraft bus (the MMS) is already in use. This invaluable practical experience must be introduced into mission planning and design activities early enough and with conviction enough to influence the course of Space Station and future spacecraft designs.

Satellite Servicing Center

Location of the satellite servicing center on the Space Station should be selected with consideration of the following:

- EVA Translation Paths
- Contamination
- Lighting
- Thermal Control
- Radiation (all kinds)
- Particle Protection.

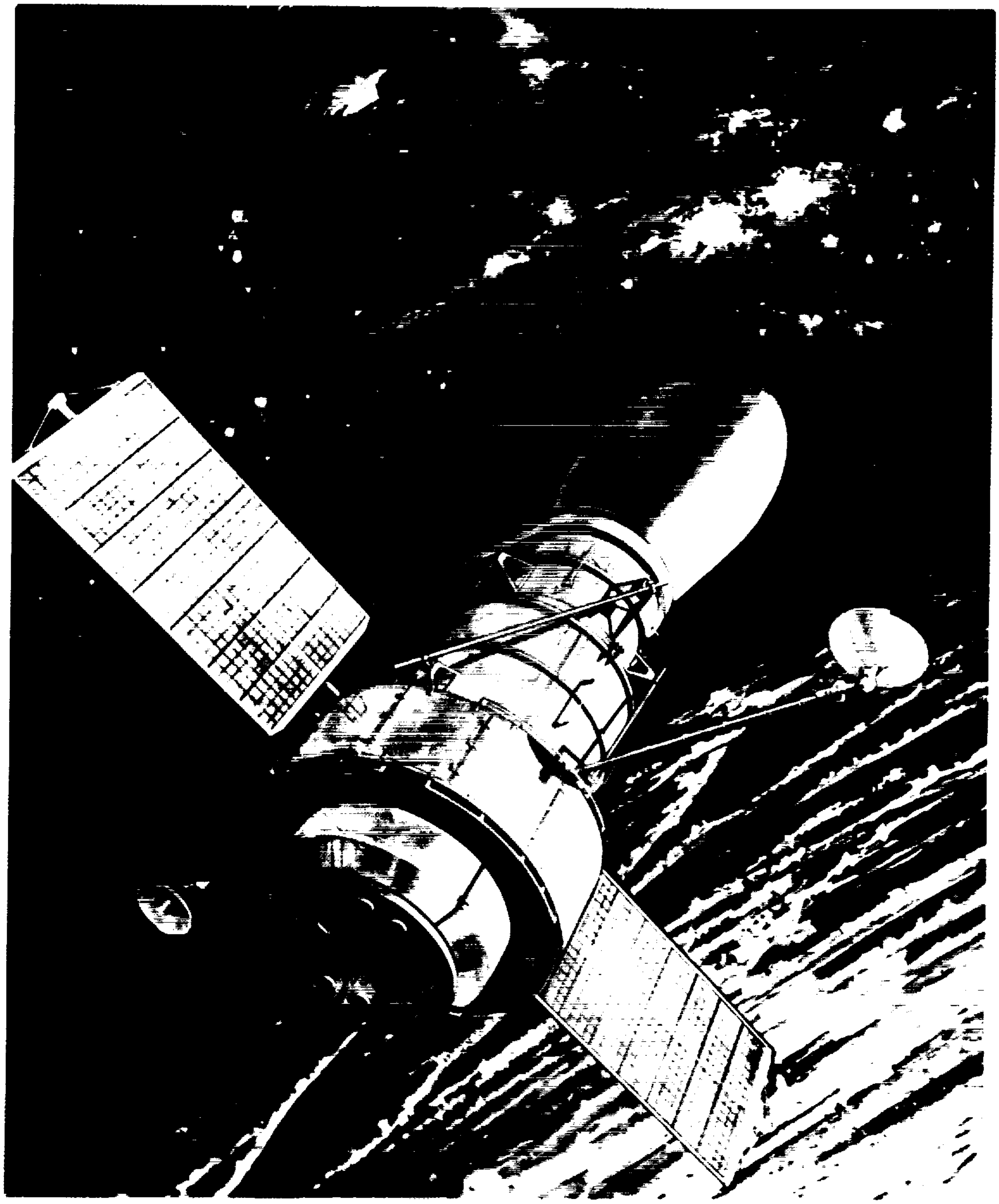

FIGURE 3.5. SPACE INFRARED TELESCOPE FACILITY (SIRTF)

Cold optics and sensors are required for sensitive observations of the processes of stellar birth, and SIRTF is designed so that superfluid helium can be supplied in space to keep the telescope within a few degrees of absolute zero. SIRTF is another candidate mission for a dedicated Space Station platform.

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The Space Station based service center should be equipped with the necessary support hardware to perform the required service activities:

- A spacecraft berthing and positioning system with tilt and rotate capability, standard berthing interface and electrical umbilical mate/demate mechanisms
- A spacecraft payload retention system duplicating the Shuttle Orbiter payload retention system and electrical interfaces
- A spacecraft/payload storage area to accommodate spacecraft awaiting servicing or Shuttle-delivered payloads to be mated to spacecraft
- Station Manipulator System with Manipulator Foot Restraint (MFR)
- Manned Maneuvering Unit (MMU)
- Refueling capability for gases, fuels, and cryogenic fluids
- Stowage sites for replacement modules, instruments, electronic hardware, and test equipment
- Outgassing sites for spares previously stored or repaired in a pressurized environment or recently arrived on the Shuttle
- Tools and tool storage areas
- EVA support equipment--foot restraints, handrails, slidewires, and tethers
- Orbital Maneuvering Vehicle (OMV) and docking port
- Advanced Extravehicular Mobility Unit (EMU)
- Accommodations for assembly and servicing of larger spacecraft
- Shirtsleeve work environment for detailed corrective and upgrading tasks (i.e., piece part and component changeout) with adequate access for science instruments and other fixable subsystems.
- Robotic system for performing routine mechanical activities without EVA requirement
- Orbital Transfer Vehicle (OTV) to support remote automated servicing of spacecraft
- On-orbit checkout equipment and crew training aids.

Spacecraft Berthing and Positioning System

A spacecraft berthing and positioning system, with tilt and rotate capability, is needed to act in concert with the station manipulator system to provide servicing access to the entire exterior of spacecraft being serviced. This system should incorporate standard berthing latches for spacecraft restraint and electrical umbilical mating drives to provide electrical power for control and monitoring of spacecraft systems. This platform should be located to provide the maximum clearance for solar arrays and other appendages. However, to minimize potential hazards to the EVA crew and/or spacecraft, these items should be retractable.

Spacecraft and Payload Retention System

A retention system duplicating Shuttle orbiter payload retention system interfaces is required to restrain Shuttle-delivered spacecraft and payloads awaiting servicing, payload/spacecraft mating, or spacecraft that are incompatible with the berthing and positioning interfaces. This system should be positionable at a variety of locations using the station manipulator system to accommodate variously sized spacecraft and payloads and to facilitate servicing operations.

Satellite Storage Area

A retention system duplicating Shuttle orbiter payload retention and Flight Support System berthing interfaces should be available for storing retrieved satellites awaiting servicing. Thermal control for the satellite will have to be maintained either through the provision of power to the satellite or through the control of its surroundings.

Station Manipulator System

A station manipulator arm, similar to that existing on the present STS, will be used in support of the following activities:

- Berthing/deploying spacecraft
- Positioning EVA crewman for maintenance activities using the Manipulator Foot Restraint
- Transporting replacement modules to/from the equipment stowage site.

The arm should be long enough to provide access to the module stowage site, to support off-loading of the Space Shuttle and transporting the replacement parts. A second arm may be required to support these functions or more complicated tasks depending on relative locations of the stowage site, Space Shuttle docking port and service center.

A Manipulator Foot Restraint (MFR) work platform should be attached to the arm. This device allows an EVA crewman to be positioned at various locations around the spacecraft being serviced. It also supports the special tooling required for repair/maintenance operations.

Manned Maneuvering Unit (MMU)

An MMU will be used by EVA crewmen to perform berthing operations, transport replacement modules to and from the stowage site, and inspect spacecraft systems.

Resupply Capability

A workstation for recharging spacecraft propellants, pressurants, cryogens, and instrument gases and fluids should be available. Transfer of the fluids could be accomplished by EVA crewmen or automated means within the servicing center. The transfer/recharge system should accommodate the standard fill and drain interfaces on existing spacecraft and future quick disconnect valves on new spacecraft with planned recharge capability.

Stowage Site

Replacement modular systems (instruments or support systems) will be transported to and from the Space Station via the Shuttle. The stowage site should be close to the berthing platform and spacecraft payload retention system to allow the station manipulator arm to be used to transport replacement items. It should be clean, thermally controlled, and unpressurized.

A hardware inventory of standard subsystems (power modules, attitude control system, batteries) should be maintained. Subsystems common to several spacecraft can then be interchanged. Faulty units would be removed and replaced with flight ready units. The faulty units then could be returned to Earth for rework and testing or they can be repaired in the shirtsleeve workshop.

Tool Storage

A tool storage facility within the servicing center would provide ready access to the tooling required to support standard servicing tasks. The tools should include Module Service Tool, power drive, and wrenches required to perform most EVA tasks. Special tooling, unique to a given spacecraft, would be delivered to the Space Station via the Space Shuttle with the replacement item.

EVA Support Equipment

The EVA servicing worksites should be equipped with handrails, slidewires, tethers and foot restraints.

Orbital Maneuvering Vehicle (OMV)

The OMV will be used as the primary mode of capture and transport of co-orbiting free-flyers to the service center docking port. Once docked, the spacecraft will be transferred to the berthing platform or spacecraft and payload retention system for servicing. Servicing may be accomplished on the OMV itself. Precautions must be taken in the Space Station design to minimize the hazard of contamination from the OMV.

Advanced Extravehicular Mobility Unit (EMU)

The EMU is a self-contained spacesuit that provides crewmen with environmental protection, life support, communications, visibility, and mobility during periods of extravehicular activity. An improved EMU system will be required to allow EVA periods of up to 8 hours per day and 40 hours per week without a required day of rest between EVAs. This will result in increased EVA time for servicing or repair activities. Improved mobility and dexterity are key requirements for Space Station era operations.

Shirtsleeve Maintenance Facility (Lab Size)

This section of the Space Station service center should include a contamination-free work environment. The shirtsleeve facility should be attached to the main Space Station elements to permit easy access, without EVA excursion. It will be used to service spacecraft modules, including science instruments.

SPACECRAFT REQUIREMENTS FOR SERVICING

Although the Space Station must satisfy many requirements to fulfill the servicing needs of satellites, each satellite must also meet certain requirements to be serviceable by the Space Station. These design and operation requirements will standardize many aspects of spacecraft servicing as well as ensuring the safety of the operations. Standardizing the capture, berthing and maintenance tasks will minimize the servicing time and the necessity for mission-unique servicing hardware. Meeting these requirements will also guarantee that a satellite will be serviceable.

Accessibility is Most Important

The most important requirement, which must be met before any satellite is even considered for servicing, is that the serviceable systems and components be accessible. EVA crewmen will need safe access (body, hand, tool, and visual) to all systems/components that will or may require servicing. Furthermore, the easier access is, the better the chance of successful servicing; EVA time and risk of damaging the satellite or the crew are minimized with easy accessibility. A good example of a system that is easily accessible for replacement is the Modular Attitude Control System (MACS), an MMS module that was replaced during the Solar Maximum Repair Mission. The Main Electronics Box, which was replaced on the same mission even though it was not designed for in-orbit servicing, was able to be replaced due to its accessibility to the EVA crewmen with the use of a few special tools. On the other hand, a satellite that is designed with inaccessible components imbedded within a structure or entangled in harnessing may not benefit from servicing.

Capture, Berthing, and Safing

The first step in servicing a satellite is its capture, which can be accomplished by using the RMS, OMV, OTV, or MMU, depending on the location and dynamics of the target satellite. The spacecraft must have a standard capture interface for the anticipated capture method(s). The standard capture interface would be an RMS grapple fixture if the Shuttle RMS is used to capture the satellite. Standard capture interfaces are not yet defined for the MMU, OTV, and OMV.

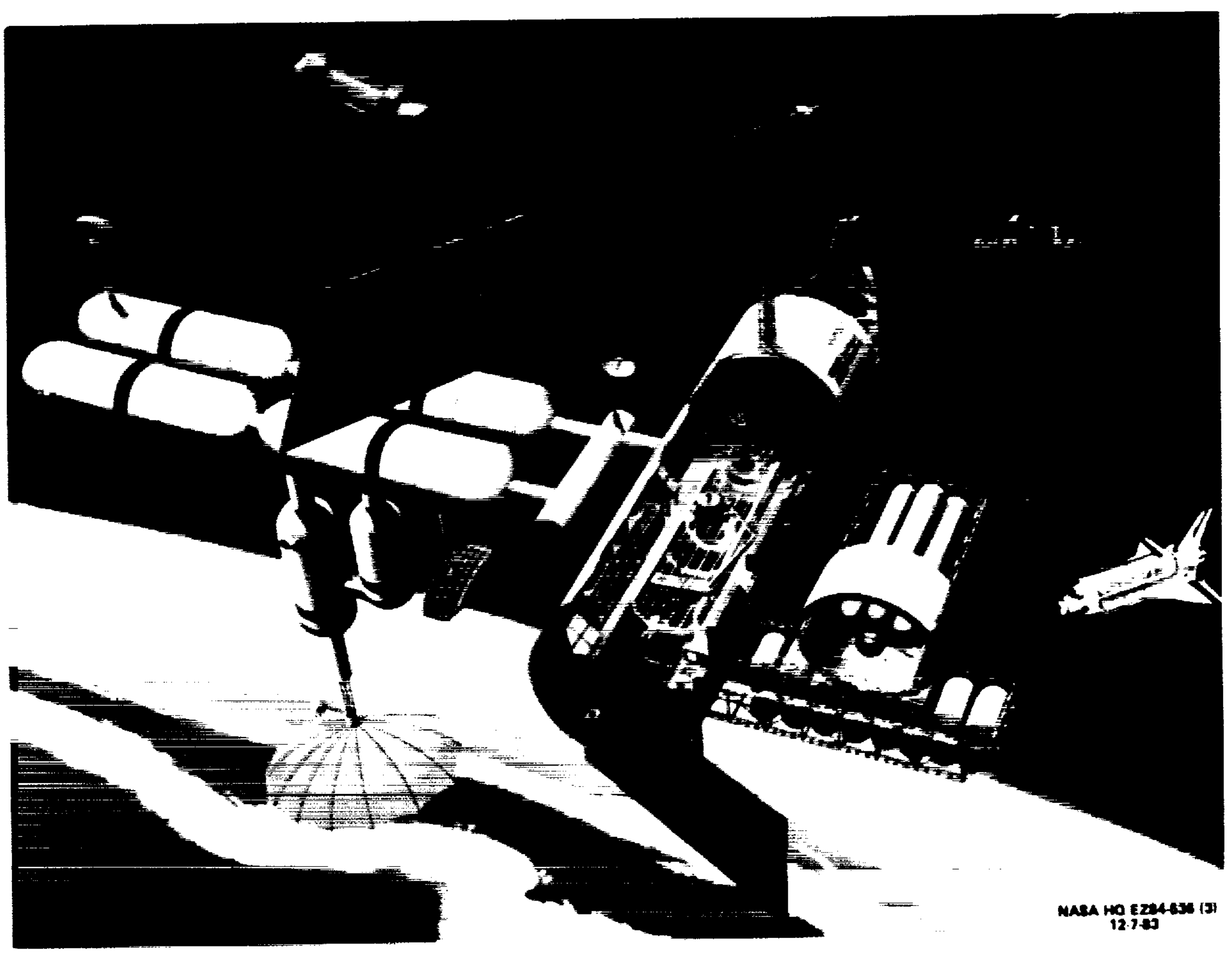

FIGURE 3.6. FOURTH-ECHELON SERVICING AT THE SPACE STATION

In Echelon Four, an entire spacecraft is brought into a pressurized compartment for servicing.

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After the satellite is captured, it will be berthed onto the Space Station servicing complex, preferably without using EVA. This will require a standard mechanical berthing interface such as that on the MMS Flight Support System (FSS) berthing platform or the Space Shuttle trunnion fitting arrangement. A standard electrical interface between the Space Station and the satellite will also be necessary to supply power to the spacecraft during servicing. Many satellites have appendages such as solar arrays, antennas, and booms that might not allow the spacecraft to fit in the envelope of the servicing center. Depending on their size and orientation, spacecraft appendages will be required to be retractable by motor and with manual EVA backup.

A satellite must not endanger the crew or Space Station during capture, servicing or deployment operations. This requires that any hazardous devices or materials on board, such as propellants, pyrotechnics, radioactive sources, or cryogenics, be efficiently rendered safe without risk to the crew or Space Station. Also, the satellite must be free of sharp edges that could snag or puncture an EVA crew member's suit.

The servicing environment for a satellite will differ from that experienced in its mission orbit and altitude. Sensitive instruments will have to be protected from harmful effects (such as light, gases, etc.) that could be incurred any time during capture and servicing. Auto-actuated protective covers may be necessary for some instruments. In addition, the spacecraft thermal system must have the capability to maintain survival temperatures for all elements of the satellite during each phase of servicing.

Modularity

As already mentioned, each system or component to be serviced must be accessible; the easier access is, the better the chance of successful servicing. In addition, a modular design for serviceable systems and components will ensure that the EVA portion of the servicing can be done efficiently and will limit the margin for error in handling, connecting, or disconnecting components.

Again, standardization of servicing equipment interfaces will ensure that the Space Station can service the satellite. The satellite must use standard hardware to interface with EVA tools. The standard hardware to be used by all serviceable satellites must be designated and defined. An example of standard hardware is the 7/16-inch hex heads used on the Space Telescope instruments and the EVA interfaces for FSS mechanical overrides. Similarly, standard interfaces for the resupply of liquids for propulsion and cryogenic systems will be required.

Benefits in Ground-Handling

As experienced by the Solar Maximum and Landsat programs during their integration and test cycles, the design of spacecraft for in-orbit repair produces payoffs for ground integration and test cycles. By designing hardware for in-orbit serviceability, ground integration and test cycles have been significantly shortened. In addition, ground troubleshooting is easier by virtue of telemetry formatting for in-orbit remote diagnostic checking.

In essence, if modules and components are designed to be changed out in a 1-hour EVA period, then the same hardware on the ground can be changed out equally as fast. By the same token, if that hardware has been designed to report back any anomalous behavior in-orbit, then the same can be done during ground tests. Finally, if serviceable hardware and software have been designed to protect themselves against either confused ground instructions or commands or related hardware failures, then the same features will exist on the ground to self-protect the system against test errors or cascading hardware failures.

Summary of Requirements on Spacecraft

In summary, early interface coordination with Space Shuttle and Space Station offices is imperative. Some design and operational requirements imposed on a spacecraft to accommodate servicing at the Space Station are as follows:

- Accessibility of systems/components to be serviced (body, hand, tool, and visual access)
- Standard capture interface--compatible with RMS, OMV, OTV, and/or MMU as necessary
- Standard latch interface for berthing in the service facility
- Standard electrical interface
- Retractable appendages--motor driven with manual override
- Capability to make safe all hazardous systems--cryogenics, hydrazine, pyrotechnics, etc.
- Capability of spacecraft thermal system to maintain survivable temperatures for spacecraft elements during servicing
- Protective covers for sensitive instruments that cannot tolerate the servicing environment
- Standard EVA requirements--no sharp corners, standard handrails, etc.
- Standard interfaces for EVA tools
- Standard interface for liquid resupply
- Modular design of systems/components that will be handled by EVA.

Spacecraft Co-orbiting Considerations

Systems that must be kept near the Space Station for servicing or for operations must be designed with careful consideration of orbital drift parameters. As the orbiting spacecraft or platform decreases or increases altitude relative to the Space Station, the precession rate will change relative to the Space Station. This differential precession will result in nodal divergence, requiring large propulsive maneuvers to correct for drift.

If frequent servicing or Space Station visits are required, then the spacecraft or platforms must possess sufficient propulsion to stay close to the Space Station node or be prepared to conduct very large propulsive burns to get back to the Space Station.

To rendezvous for servicing, it is not enough for a satellite to have the same inclination as the Space Station; it must have very nearly the same plane. Because the Earth is not a perfect sphere, the planes of all satellites change slightly with each orbit, with planes changing more slowly at higher altitudes. In general, we would like to orbit our astrophysics missions at higher altitudes than the Station, and if we orbit them 150 kilometers higher, their orbits will align with that of the Space Station every 2 years. This is a reasonable interval for servicing, but it has important implications for planning, scheduling, and funding satellite servicing missions. They will become like planetary missions with specific mission windows that appear infrequently. It also means that the Shuttle will remain the primary facility for contingency servicing activities.

CONCLUSION

In summary, the orbital servicing potential of the Space Station represents a significant opportunity for us to increase the return on our spaceflight investments while correspondingly increasing our ability to perform longer and more productive spaceflight missions. This volume attempts to define this capability, while it is yet in the germinal stage, by developing of a set of user and Space Station requirements. Planning at such an early stage will ensure that all potential features are considered, so that future reuse of spaceflight systems will be as commonplace as one-time use is today.

APPENDIX ON SATELLITE SERVICING FROM THE SPACE STATION

Nowhere will the impact of a permanently manned Space Station be felt more than in the servicing of satellites in space. The very idea was made possible by the Space Shuttle and becomes a powerful thrust in the use of space with the advent of a manned base in orbit. This comes at a time when NASA's Astrophysics Program is developing major observatories for investigating the universe from infrared to gamma rays, and after we have repaired our Solar Maximum Mission from the Shuttle. This tremendously successful mission shows just the beginning of what we can expect as the capabilities of the Shuttle develop and the manned base eventually comes into operation.

Already, the Astrophysics Program is planning to use this new capability to assure and extend the lifetimes of future missions. Our four major new observatories--the Hubble Space Telescope, the Gamma Ray Observatory, the Advanced X-Ray Astrophysics Facility, and the Space Infrared Telescope Facility--are being designed for servicing on orbit. Other missions can benefit significantly from orbital servicing at the Space Station--in particular, a number of scientific payloads attached to the manned base and a whole fleet of small astrophysics free-flyers.

This appendix presents an overview of the types of astrophysics missions--large observatory, manned base, small free-flyer--a brief description of several particular scientific payloads, and a brief consideration of the servicing functions and requirements anticipated for each type of mission. Detailed mission descriptions appear in companion volumes produced by the June 1984 workshop on Astrophysics Utilization of the Space Station.

LARGE OBSERVATORIES

Hubble Space Telescope

The premier space observatory for optical and ultraviolet astronomy will be the Hubble Space Telescope (HST), named for Edwin P. Hubble, the astronomer credited with discovering the awesome size of the universe. The Hubble Space Telescope, planned for launch in 1986, will carry five instruments for ultraviolet and visible light research. It will see seven times farther than previous optical telescopes, increasing our survey of the universe to a volume 350 times greater than before, and will photograph in space ten times more sharply than previous telescopes. Sophisticated fine guidance sensors will make astrometric measurements of stellar positions with unexcelled precision to as faint as the 14th magnitude. The present payload is designed for in-orbit replacement and future instruments are expected to include cryogenic infrared sensors. The Hubble Space Telescope is managed by Marshall Space Flight Center, which is also responsible for maintenance and refurbishment; Goddard Space Flight Center is in charge of scientific instruments and mission operations. Hundreds of astronomers will visit the Space Telescope Science Institute in Baltimore, Maryland, each year to perform research with the telescope.

Through quantum leaps in sensitivity and spatial, spectral, and time resolution, the Hubble Space Telescope is expected to make major breakthroughs in fundamental aspects of cosmology, astrophysics, and planetary science. The basic telescope design was driven by the cosmological objectives, which include establishing a definitive distance scale of the universe, reliably estimating the age of the universe, and determining whether the universe is "open" and will expand forever or is "closed" and will eventually halt its expansion to begin a great, perhaps final, collapse that would destroy all the galaxies in space.

The Hubble Space Telescope was designed for in-orbit EVA servicing by Space Shuttle crew. However, this concept is limited to the exchange of a few Orbital Replaceable Units (ORU). Eventually instruments are to be replaced by second-generation, more advanced devices. Servicing at the Space Station in a shirtsleeve environment would allow repair of spacecraft subsystems that are not ORUs or repair of ORUs (such as scientific instruments) for which backups may not be available on a timely basis.

The planned alternative is to return the telescope to the ground for servicing. This is increasingly regarded as unacceptable since return will precipitate serious contamination and affect delicate optical and mechanical adjustments. It is certain that return to the ground would greatly increase the scope, cost, and time of necessary rework. Further, return to the ground is expected to interrupt the scientific program of the telescope for about 2 years at a time, a prospect viewed with alarm by the astronomy community.

Since the Hubble Space Telescope is already largely constructed, little can be modified now. Thus, the preservation of this $1-billion resource necessarily places requirements on the Space Station for servicing rather than vice versa. In particular, a contamination-free shirtsleeve environment (comparable to a Class 10,000 clean room) is required. Second generation instruments such as two-dimensional spectrographs are expected to greatly increase the data storage and transmission requirements on the telescope. This might mean that spacecraft subsystems not built as ORUs, such as telemetry transmitters, would have to be replaced or upgraded at the Space Station. A Space Station service center could provide the Hubble Space Telescope a logistics base for quick-response maintenance and repair activities to keep the telescope in continuous operation.

Gamma-Ray Observatory (GRO)

Gamma rays are the form of electromagnetic radiation with the shortest wavelengths and the highest energies, and gamma ray astronomy represents a window on many of the most energetic phenomena in the universe. As an example, gamma ray radiation seen from the direction of the center of our galaxy originates from matter-antimatter annihilation, and the time variability of this radiation suggests the presence of a massive black hole at the galactic nucleus. Other sources of cosmic gamma rays include supernovae, pulsars, quasars, and interactions of cosmic rays with matter in interstellar space. Some gamma rays, such as the high-energy radiation from some sources and the low-energy gamma ray bursts, have origins that remain mysterious.

To study gamma rays of all energies and from the whole sky, NASA is developing the Gamma Ray Observatory (GRO), which will do the first complete survey of this high-energy portion of the spectrum. This observatory carries a complement of four instruments.

The Gamma Ray Observatory is being designed with a capability for maintenance and repair either by the Shuttle or at the Space Station. The primary goal of this maintenance is the extension of the life of the observatory beyond its 2-year baseline. Particularly in a field such as gamma ray astronomy where relatively little is already known, an extended mission provides tremendous opportunities for scientific return, such as:

- The study of long-term time variations of sources
- Detailed studies of discoveries made during the initial survey part of the mission

- Deep surveys of extragalactic regions to search for distant objects
- Additional chances to observe rare events such as novae or supernovae.

The key to this extended mission is refueling of the spacecraft, since the low orbit of the Gamma Ray Observatory requires regular reboosting. Additional benefits of servicing are the possibility of repair if a malfunction should occur beyond what is already allowed for by redundancy, replacement of either spacecraft or instrument modules, and perhaps even replacement of an instrument with an upgraded version or a totally new detector concept. This last option would be open to the Gamma Ray Observatory only if the Space Station has relatively sophisticated repair capabilities, since the instruments themselves are not designed for simple replacement.

The Advanced X-Ray Astrophysics Facility (AXAF)

The Advanced X-Ray Astrophysics Facility (AXAF) will study the universe in a unique way, providing x-ray pictures of the farthest reaches of the universe with a depth and detail comparable to those obtained by the most advanced optical and radio telescopes. More importantly, because these pictures will be in x-rays rather than radio waves or visible light, AXAF will provide a new look at the universe.

A vast number of scientific studies can be accomplished only by looking at x-rays. For example, a hot gas at temperatures of millions of degrees fills the space between galaxies comprising the great clusters--groups of hundreds of galaxies bound to each other by the force of gravity. This gas is so hot that it can be observed only in x-rays. Huge amounts of this gas are in the galaxy clusters, and x-ray observations of it map the clusters' gravitational potential. In addition, the mass of the hot gas contributes significantly to the total mass of the clusters and thus to the total mass of the universe.

AXAF will be an x-ray observatory built around a large-area, high-resolution, grazing-incidence x-ray telescope. Designed to operate in space for at least 15 years, AXAF will be operated as a major national facility with the majority of the observing time set aside for guest investigators. This long lifetime will provide the astronomical community with a facility capable of performing the many observations now known to be necessary on the basis of previous investigations and the questions raised by them, and also capable of pursuing, in coordinated observing programs, those new discoveries which AXAF will surely make.

A variety of x-ray instruments can be placed at the focus of the AXAF telescope. Some of these instruments may require consumables for their operation, such as cryogens for solid state devices and gas for proportional counters. These point to the need for in-orbit servicing to minimize downtime and to avoid placing excessive demands on the AXAF spacecraft, such as providing the weight and volume for a 15-year gas supply.

In general, the in-orbit servicing requirements for AXAF fall into three major categories:

- Maintenance of the orbit
- Replenishment of consumables
- Repair and/or replacement of spacecraft and instrument systems or subsystems.

Of these, orbit maintenance is absolutely essential for the long duration (15 years) of the mission. This orbital station-keeping can be achieved with an integral propulsion system, a remotely operated orbital maneuvering vehicle (OMV), or the Space Shuttle. These first two options can be supported from an orbiting Space Station. Various orbital altitude maintenance strategies have been proposed, ranging from relatively infrequent reboosts of AXAF from approximately 250 nautical miles to approximately 350 nautical miles every 3 to 5 years to more frequent orbit adjustments of AXAF from approximately 250 nautical miles to approximately 270 nautical miles every 6 to 12 months. Cost trade-off studies are needed in order to evaluate these approaches.

To ease the in-orbit servicing task, the AXAF spacecraft will either be designed to be common to several of the Astrophysics missions, including SIRTF and either HST and GRO, or it will make use of standard Space Station platform modules. This approach will provide a significant degree of commonality between spares, test equipment, and crew training required to support the servicing of astrophysics missions.

The replenishment of consumables is associated mainly with the AXAF scientific instruments. On board gas and cryogen supplies will most likely be limited by size and weight restrictions. The instrument designs must permit replenishment with minimum effort. This might involve fully replaceable subsystems and/or standard fittings and couplings that can be applied to a number of instruments and spacecraft. Co-scheduling replenishment with orbital altitude adjustments reduces the number of servicing activities. However, while orbital adjustments can be entirely remote (OMV or integral propulsion), replenishment will most likely necessitate a rendezvous and an EVA.

The repair or replacement of AXAF components provides a means for recovering from malfunctions of critical systems and for upgrading the observatory capabilities. Similarly, the changeout of instruments for upgrading to newer, more sensitive detectors can be carried out on a scheduled basis, with consolidation of other in-orbit servicing activities. These repair/replacement activities will require a rendezvous with AXAF and an EVA. Advantages of Space Station servicing involve shorter response times to emergencies, simplified service mission planning, and the capability to stockpile parts. The last point is especially true if there are standard units that can be used in several spacecraft flying in similar orbits. These might include power distribution systems, attitude control systems (star cameras and rate gyros), and telemetry systems.

In summary, in-orbit servicing is essential to the success of the AXAF mission, and it is primarily driven by the long lifetime of the observatory. This includes orbital station-keeping, replenishment of consumables, and repair or replacement of AXAF elements. These activities can be carried out via the Space Station, and they have no requirements that are unusual or unique, compared to other observatory-class missions such as the Space Telescope. The development of an orbital altitude strategy appears to be an important driver for in-orbit servicing.

Space Infrared Telescope Facility (SIRTF)

The discoveries of the first infrared survey of the sky, carried out by the IRAS satellite, are just beginning to reach across astrophysical community, and they are showing us things never before seen. The infrared traces the structure and evolution of bodies at temperatures between 10 and 1,000 K. The galaxy is transparent to this radiation, and one is struck by how thin the region of star formation is in our galaxy compared to the stars of the Milky Way seen at night in visible light. (See the maps in Volume 1.) As in other spiral galaxies, most of the bright stars in our galaxy are confined to a disk with the proportions of a long-playing phonograph record. Our view at night is limited to the nearest few hundred light years; if there were no dust, we would be dazzled by the light from stars up to a thousand times farther away, nearly all confined to the narrow plane revealed in the infrared.

Among other discoveries, IRAS found a ring of dust and debris about the star Vega that is likely to be the by-product of the formation of planets. There may be many such stars and debris systems in our galaxy. IRAS appears to have a recorded at least several dozen, but the best instrument for a sensitive search will be the Space Infrared Telescope Facility (SIRTF). It is not enough to see that a star has an infrared excess; the extent and spectral signature of the debris must be resolved to confirm its nature. SIRTF will have at least a factor of 10 times better angular resolution than IRAS, and consequently will provide detailed infrared pictures of even the faintest infrared sources.

Because it operated in space and its telescope was cooled to below 4 K, IRAS had a sensitivity far beyond any previous instrument, and it will not be possible to view the objects in the IRAS survey catalog again until cryogenically-cooled telescopes return to space. SIRTF is a 1-meter class, cryogenically-cooled infrared telescope, designed for long-duration operation in Earth orbit with imaging and spectroscopic instruments. SIRTF will be the most sensitive of all the infrared telescopes planned for the 1990's. Its wavelength range will go beyond the 8 to 120 micron coverage of IRAS to the entire infrared band from 2 to 200 microns. Where they overlap, SIRTF will be 100 to 1000 times more sensitive than IRAS.

The gain in sensitivity of SIRTF over IRAS results from three major differences. First, IRAS was primarily a survey instrument which swept rapidly across the sky, while SIRTF will be a true observatory, carrying a variety of focal plane instruments and capable of extensive observations of a single target. Second, the sensitivity and sophistication of infrared detectors have increased dramatically over the last several years. Some of the SIRTF detectors will be spectrometers providing spectral resolution between 100 to 1000 times greater than the broad "color" resolution of IRAS.

The final difference will be the duration of SIRTF. With resupply of cryogens in orbit and servicing of other subsystems, it is entirely reasonable to design SIRTF for a 10- or 15-year mission. This will allow the astronomical community maximum utilization of the tremendous capability provided by SIRTF. While replacing and upgrading the scientific instruments within SIRTF is desirable, this capability will be difficult because the entire telescope is cryogenically cooled. These servicing activities may only be possible with a Space Station facility.

ATTACHED PAYLOADS ON THE MANNED BASE

The Space Station can be used as a mounting platform and service center for externally attached astrophysics payloads. Because it provides long-term stability, a relatively low contamination environment, a large mass-support capacity, and ready access for servicing, the Space Station is well-suited as a base for large instruments requiring long-duration operations and periodic maintenance.

Instruments for research in two astrophysics disciplines--solar physics and cosmic ray physics--have been identified as candidate attached payloads. Servicing these payloads primarily will involve frequent replenishment of consumables (at about 6-month intervals) and occasional instrument change-out to upgrade a facility.

To study fundamental physical processes on the Sun, solar physicists desire simultaneous, long-term observations over the entire electromagnetic spectrum. Such research requires an ensemble of instruments making coordinated observations within different spatial, spectral, and temporal parameters. The Space Station is a good platform for a solar instrument complement pointed at the same target of observation. It also can support expansion of the complement, by instrument changeout, into a larger, more mature observatory facility. The Advanced Solar Observatory (ASO) will develop on the Space Station in this evolutionary fashion from the Solar Optical Telescope and the Pinhole/Occulter Facility.

Precise investigations in cosmic ray physics require long observation periods, very large detectors, and stable pointing away from Earth. The flux of cosmic rays near Earth is of great interest, since these high-energy charged particles contain information about their sources, the interstellar medium, and the acceleration processes that enable them to travel vast distances through space. The manned base provides not only a suitable place to mount very large cosmic ray instruments but also a facility for changing their configurations, resupplying consumables, and retrieving exposed materials on a timely basis. The Transition Radiation Ionization Calorimeter (TRIC) investigation, a modified version of the Spacelab Cosmic Ray Nuclei Experiment, probably will be the first attached payload in the discipline of cosmic ray physics to use the Space Station's capabilities.

WORKSHOP ON

ASTROPHYSICS UTILIZATION OF THE SPACE STATION

Panel on

Servicing Astrophysics Missions at the Space Station

Mr. B. Ronald McCullar, Chairman

Mr. Michael Bay
Mr. Richard Cable
Mr. Frank Cepollina
Dr. John Dickey
Mr. Ronald R. Felice
Ms. Jean C. Folse
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Dr. Phillip Schwartz
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Mr. James Steincamp
Dr. David E. Thompson
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